2. CONTROL OF VARIABLE-GEOMETRY SUPERSONIC INLETS FOR TURBOJET APPLICATIONS

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INTRODUCTION

Use of the turbojet engine at supersonic flight speeds introduces the need for providing means of efficiently matching the inlet air flow to the engine air flow. This subject has been comprehensively treated in the literature, and the penalties of mismatching are by now familiar. Subcritical inlet operation not only increases the external drag but generally imposes the additional problem of engine operation during inlet pulsing. Supercritical operation, on the other hand, not only introduces a loss in cycle efficiency due to reduced inlet pressure recovery but, as discussed in the previous paper, often imposes increased inlet air-flow distortions on the compressor.

Variation of inlet geometry, as illustrated in figure 1, has often been suggested as a solution to the matching problem. Typical of such proposals (ref. 1) are the translating spike or the variable ramp in the case of the two-dimensional inlet, and the variable-area bypass. Used separately, each can provide a degree of spillage for the excess air not required by the engine. Used in combination, the bypass is employed to spill excess air, whereas the spike is generally positioned for minimum inlet drag. In either case, some intelligence must be provided for the system positioning these variable-geometry features to obtain the best possible performance from the inlet-engine combination.

It is the purpose of this paper to discuss some of the control concepts applicable to the variable-geometry inlet and to evaluate the experimentally observed results of control systems based on these concepts.

SYMBOLS

H pitot pressure, lb/sq ft abs

M Mach number

p static pressure, lb/sq ft abs

x normal-shock distance from cowl lip, ft

α angle of attack, deg

θ_l angle between line joining spike tip and cowl lip and inlet centerline, deg

Subscripts:

r reference

s sensor

0 free-stream

2 diffuser exit, station immediately ahead of bypass

DISCUSSION

Clues as to the selection of some measurable quantity indicative of the mismatch between the engine and the diffuser are available from the curves presented in figure 2. The diffuser total-pressure recovery generally reaches its maximum at approximately the same corrected air flow that produces maximum thrust minus drag. The diffuser-exit Mach number varies essentially linearly with corrected air flow and is single-valued at the desired operating point. The normal-shock position is sensed by the large static-pressure rise that occurs as the normal shock passes a pressure pickup located at the desired shock position.

Control systems based upon the signals generated by each of these three parameters have been investigated. However, since the diffuser-exit Mach number and the normal-shock-positioning systems appear most attractive, only they will be discussed in detail.

The experimental work was performed in full scale in the Lewis 8- by 6-foot supersonic tunnel. A nacelle-mounted installation of a J34 turbojet engine was operated at stream Mach numbers to 2.0. Photographs of the configuration are given in figure 3. The inlet was provided with a translating spike and a variable-area bypass, the discharge of which is illustrated. The bypass air was collected through slots located circumferentially around the diffuser outer wall. Either spike or bypass could be used to spill approximately 20 percent of the maximum inlet capture mass flow. The bypass door was positioned with a hydraulically actuated servo system, whereas spike translation was accomplished with an electrically driven mechanical system. The engine fuel control was removed, and a manually operated fuel throttle substituted. Also illustrated in figure 3 are the completely cowled nacelle as tested and the nacelle with the cowling removed, exposing the engine and, along the leading edge of the support strut, the bypass drive mechanism.

If the diffuser is considered to end just ahead of the bypass, then the flow through the inlet and also the diffuser-exit Mach number may be varied by either a change in engine rpm or bypass door position. The results obtained by controlling the diffuser-exit Mach number M_2 with

bypass door position are illustrated in figure 4(a). The variation in diffuser pressure recovery is plotted as a function of M_2 for free-stream Mach numbers M_0 of 1.8 and 2.0. The dashed portion of the curve represents an inlet pulsing region. For the case under consideration, optimization of thrust minus drag occurs at the M_2 values indicated. Since optimum M_2 generally varies with M_0, a preset schedule of M_2 as a function of flight speed is required.

The ratio of static to total pressure at the diffuser exit of which the Mach number is a function was selected as the actual control input signal. The upper curve of figure 4(a) illustrates the variation in this pressure ratio with M_2 and indicates the value of the ratio for any desired M_2. If the measured value of the ratio falls above the control setting, the bypass is opened; if it falls below, the bypass is closed. Since turbojet engines operate at reasonably high compressor-inlet Mach numbers, good accuracy is to be expected in obtaining this pressure ratio.

A schematic diagram of the actual control system is given in figure 4(b). The pressures were measured with transducers and electrically divided. The ratio was then compared with the preselected control value and a corrective signal supplied to the servo actuating the bypass door. As previously mentioned, this preselected control value must, in general, be scheduled with flight speed.

The conditions set by the control system are indicated by the data points. The scatter corresponds to approximately ±5 percent of diffuser corrected air flow and was the result of using a single tube to measure diffuser-exit total pressure. Shifts in total-pressure profile with engine rpm caused this single measurement to deviate from the average. Additional profile variation is to be expected from changes in angle of attack and M_0. It is apparent that a total-pressure averaging technique (see, e.g., ref. 2) must be employed if the diffuser-exit Mach number control system is to be successful.

A system that appears to have a much wider control application than the one just discussed is normal-shock positioning. The optimum normal-shock position does not generally vary with flight speed or altitude, and the need for a schedule with operating condition is eliminated. The key to the successful operation of the normal-shock-positioning system is the signal strength generated across the shock and the accuracy possible in using this signal to set the shock location. A schematic diagram of the normal-shock control system investigated is given in figure 5(a). To avoid interference with the boundary layer generated on the spike and also to avoid sensor movement with spike translation, the normal shock sensor p_s was located at the cowl lip. A reference pressure orifice p_r was

placed near the spike tip well forward of the region of influence of the normal shock. Conventional wall static-pressure measuring techniques were utilized in each case, with orifices approximately 1/16 inch in diameter. A differential pressure transducer emitted an electric signal proportional to the difference between the sensor and reference pressures. This difference was compared electrically with the desired preset control value and the error signal used to drive the bypass door open or closed.

Tests were run at two Mach numbers, 1.8 and 2.0, and over a 20-percent variation in engine rpm. The results are summarized in figure 5(b), where the diffuser pressure recovery and the control signal are plotted as functions of the diffuser corrected air flow. The dashed lines represent the control setting, and the data points are the steady-state operation set by the control. As both engine rpm and flight Mach number were varied, the control adjusted the bypass door to maintain the normal shock at the position selected. The small scatter is within the accuracy of the air-flow measurement, and it may be concluded that satisfactory control was obtained.

In addition to the steady-state operation, the transient response of the system is also of importance. Major difficulty might be expected during a transient which places the inlet in its subcritical operating region, for during this period the inlet is generally pulsing, the air flow oscillating, and the normal shock periodically passing ahead of and behind the sensing orifice. A severe test of any control system would be to disturb the inlet into a pulsing region and then observe the control action. A typical response of the system described in figure 5 to a disturbance into the subcritical region is illustrated in figure 6. In the upper part of the figure are the instantaneous values of the control error signal voltage, the bypass door position, and the diffuser-exit static pressure. By manually overriding the control, the bypass was closed, causing the inlet to enter a buzz region and, as illustrated by the pressure-recovery - mass-flow characteristic in the lower part of figure 6, to spill 10 percent of its maximum capture air flow. A regular diffuser-exit static-pressure variation of 16 cycles per second resulted. The amplitude of this variation was 170 pounds per square foot and represented 12 percent of the mean pressure. The trace of the sensor voltage signal reveals the periodic passing of the normal shock across the sensor. The peaks represent the normal shock behind the sensor probe and the valleys ahead. Fortunately, the nature of buzz is such that the shock is ahead of the sensor for a longer period than behind. The control was turned on at the point indicated on the time scale. The desired operating condition was restored by repositioning of the bypass door to 90 percent of its displacement in 0.22 second, permitting only three cycles of pulsing. The slight reversal in door direction during the period of control action is due to the erroneous signal introduced periodically because of pulsing.

Satisfactory action was also obtained when the operating condition was manually displaced into the supercritical region to the right of the control point. Moreover, with the control on, even large steps in engine fuel flow could not drive the inlet into the buzz region.

For convenience in discussion, only control systems and results for the variable-area bypass were considered in detail. These same input-parameter principles can be and were applied to the translating spike with equally satisfactory results. Normal-shock-position sensing, for example, was applied as illustrated in figure 7(a). The difference between the sensor p_s and reference p_r pressures was compared with the control setting, and the error signal used to actuate the motor for repositioning the spike. If θ_l be defined as the spike-tip projection angle, the angle between the spike tip and the cowl, then the desired variation in θ_l with engine rpm for both M_0 of 2.0 and 1.8 is given by the solid lines in figure 7(b). These solid lines represent the condition for minimum drag consistent with maximum inlet pressure recovery. The data points that fall about the lines represent the steady-state spike position set by the control as the engine speed was varied. The data indicate that this control system set and maintained the spike position within 1° of that desired.

The normal-shock-positioning system, whether utilized for controlling either a translating spike or a variable-area bypass, operated, as illustrated on the left side of figure 8, from an input signal generated by a probe static orifice at the cowl lip. The difference between the pressure measured by this probe and the reference orifice, conveniently placed near the spike tip, can be divided by the ambient pressure p_0 to nondimensionalize the number. Values of this normal-shock-position parameter are plotted for normal-shock positions ahead of and behind the sensing orifice in terms of the percent deviation in corrected inlet air flow from the desired value. Data are presented for M_0 of 1.6, 1.8, and 2.0. The value of the parameter was near zero when the shock was downstream of the sensor orifice and rose as the shock moved forward and crossed the orifice. The desired value for the parameter was selected along this rise, and the control system was designed to maintain this value by proper actuation of the variable feature being controlled.

Selection of the value of the parameter for optimum performance at one flight speed can result in somewhat inferior performance at other speeds. In fact, at low speeds (M_0 = 1.6, e.g.), the change in parameter with normal-shock position provided a poor control signal. Attempts have been made to improve the quality of the control input signal by variation in sensor design and location. The best results thus far achieved (ref. 3) are summarized on the right side of figure 8.

A total-pressure tube facing downstream was immersed in the flow near the inlet lip. Advantage could thus be taken of the base pressure effect to increase the signal strength and reduce the value of the parameter below zero when the normal shock is located downstream of the sensor. It is apparent from the results obtained with this sensor that a single control value of the parameter can be selected that will set the desired inlet air flow over the complete M_0 range covered. Moreover, since the curves fall below zero at all speeds, the control value can be conveniently set at zero. Thus, p_s is always set equal to p_r, regardless of altitude, and no altitude compensation is required.

Thus far, the discussion has been limited to the isolated inlet control system. In the practical application it appears that two control systems will be used, one for the engine and the other for the inlet, and that some form of interaction is to be expected between them. Basic in any such interaction is the dynamic behavior of both the engine and the inlet as well as of their respective control systems.

The diffuser control is fundamentally limited in the quickness with which it can respond to disturbances. Among these disturbances might be changes in angle of attack or Mach number and changes in engine speed arising from manipulation of engine thrust. A simple way of looking at it is to consider, for example, a disturbance caused by a change in bypass door position. The fundamental limit on speed of diffuser control arises from the fact that the control signal does not change immediately after the bypass door position is changed. This phenomenon is schematically illustrated in figure 9, which gives the time history of shock position and diffuser-exit static pressure following a sudden change in bypass door area.

The normal shock does not begin to move immediately, but only after an initial delay called the "dead time." Once it begins to move, the shock position follows an asymptotic-type curve to its final position. The dead time is the minimum time it would take an acoustic signal to reach the shock sensor after a disturbing influence has been exerted. For the case illustrated, it is the time required for a pressure wave to travel from the bypass door to the normal shock. The dead time is quite short, can be analytically predicted (ref. 4), and for the full-scale configuration investigated amounted to 0.012 second. The value of the dead time influences the allowable steepness of the control input parameter variation without causing control oscillation. Referring to figure 8, it becomes apparent that the control system evaluated did not oscillate in spite of the very steep slope of the parameter in the region of the control setting due, in part, to the short dead time.

In addition to the dead time where nothing happens, a second delay, a lag, was observed. This lag is the time required for the diffuser to

to fill up, or empty, as the case may be, causing the diffuser-exit static pressure to change and driving the normal shock to its new position. For the configuration investigated, the normal shock lagged behind the bypass door movement by about 0.04 second.

Obviously, the delay in movement of the normal shock limits the quickness of control response, and hence limits the protection the inlet control affords in the presence of fast disturbances. The extent of the protection provided following a change in engine throttle position, for example, is illustrated in figure 10. In the upper sketch, the diffuser total-pressure ratio is shown as a function of bypass door position for two engine speeds. If the engine were at 90-percent rated speed and the door position set for maximum pressure recovery, a quick change in engine speed to rated would cause the pressure recovery to fall. With an inlet control, the pressure falls a smaller amount, assuming values along the broken line back up to peak recovery.

The effects of diffuser dead time and speed of the bypass door servomotor on the drop in diffuser pressure are shown in the lower portion of figure 10. The ordinate is the error with an inlet control divided by the error without the control. The abscissa is the speed of the servomotor with increasing numbers representing faster response. The actual numbers correspond to the natural frequency of the servomotor in radians per second. These curves are the result of an analog study based on typical engine and control system characteristics. The engine and diffuser tested are represented by the data point at a dead time of 0.012 second and a servomotor response of 18. With a control on the engine, the inlet control system employed would cut the error to approximately 40 percent of its peak value. If this is considered insufficient, it may be further reduced by increasing the speed of the servomotor, reducing the dead time of the diffuser by appropriate hardware changes such as reducing its length or moving the bypass nearer the cowl lip, or by slowing down the response of the engine control system, permitting the inlet control system to keep up with it.

CONCLUDING REMARKS

Although the data presented in this discussion were limited to zero angle of attack, control systems based on the parameters described have been successfully operated to $+10^{\circ}$, the maximum investigated. This was done by placing the pressure pickups along the horizontal centerline of the inlet. Moreover, although only data for axially symmetric inlets were presented, the same parameters may be employed with a side inlet.

The work in this relatively new field may be summarized by stating that techniques are available for controlling the variable-geometry inlet to provide for improved inlet-engine matching. The particular control

parameter selected depends upon the requirements of the specific application. However, because it appears that separate control systems may be employed for the engine and inlet, consideration must be given the problem of their interaction. As part of this problem, additional study of the dynamic behavior of diffusers is required. There is also a need to find new inlet control parameters as well as to improve the techniques of using the existing ones. Much of this work can be done with properly instrumented scale models of the inlet alone, and work is continuing on such models as well as with the full-scale inlet-engine combination.

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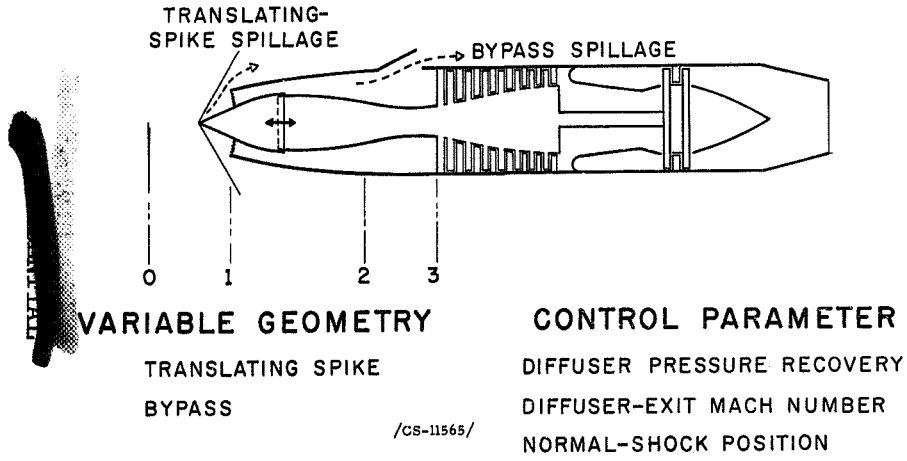

Figure 1

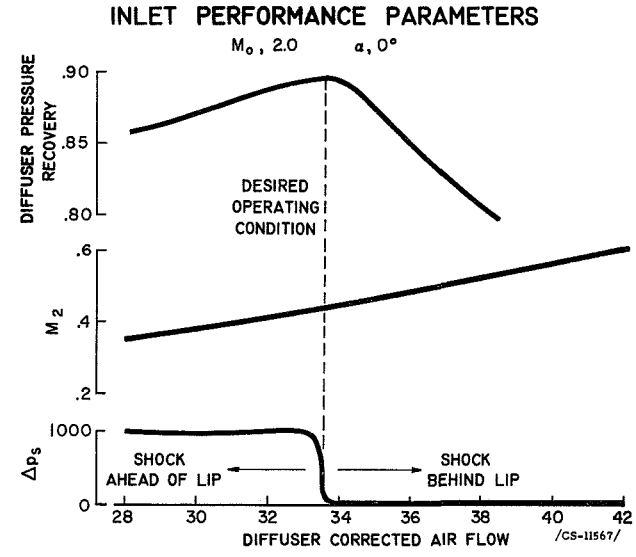

Figure 2.

J34 TEST NACELLE

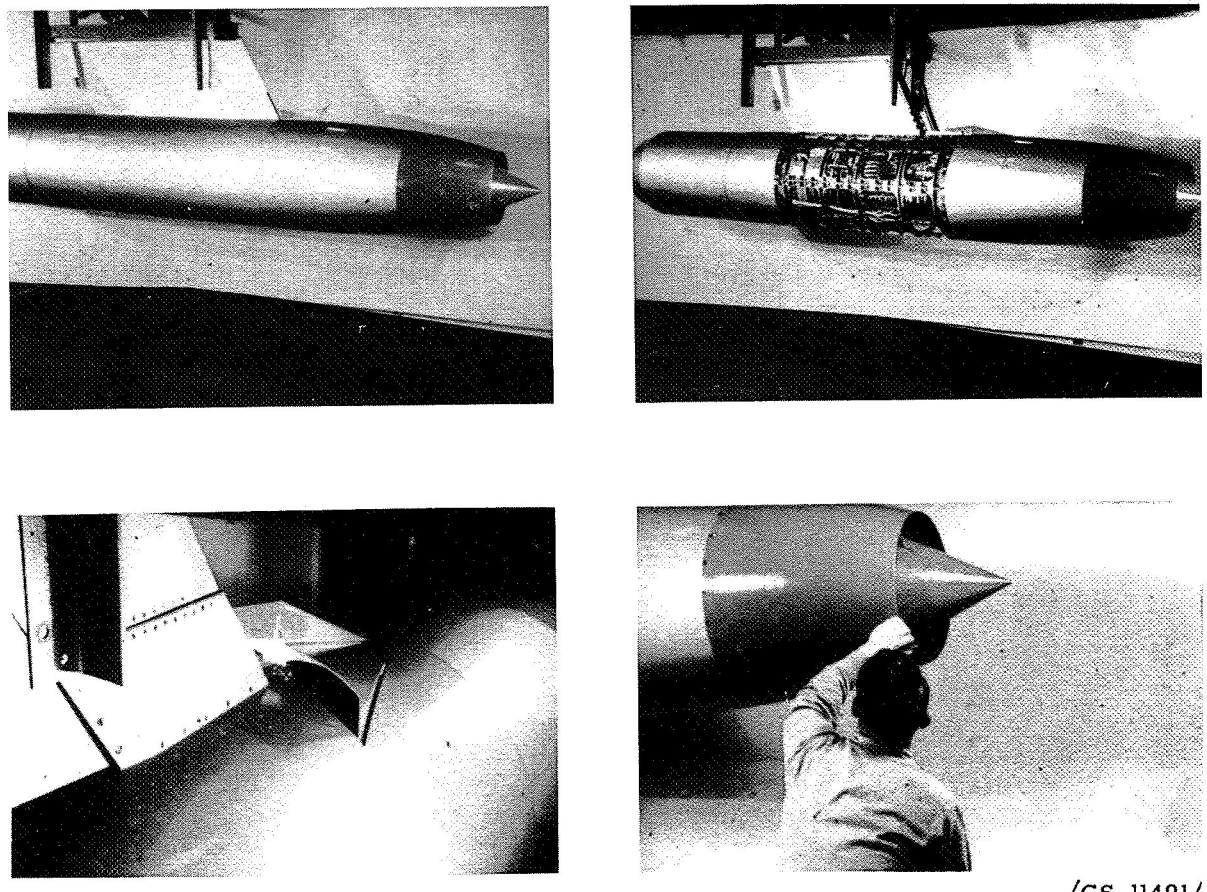

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Figure 3

DIFFUSER-EXIT MACH NUMBER CONTROL OF BYPASS

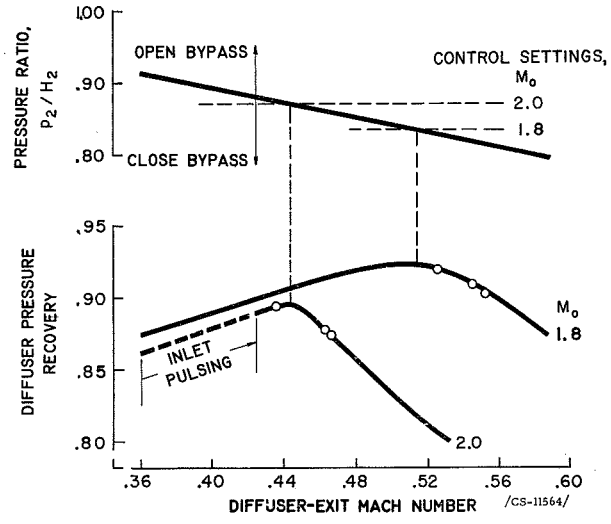

Figure 4a

DIFFUSER - EXIT MACH NUMBER CONTROL OF BYPASS

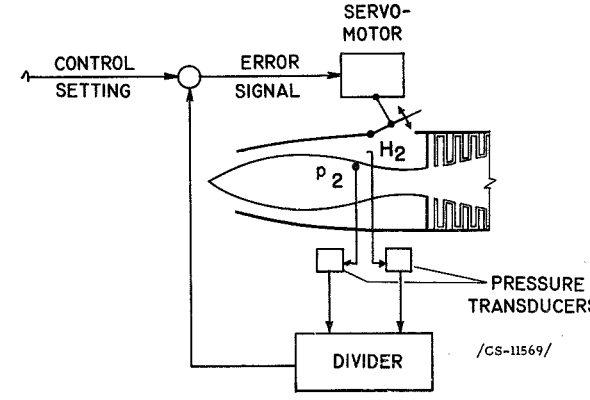

Figure 4b

NORMAL-SHOCK CONTROL OF BYPASS

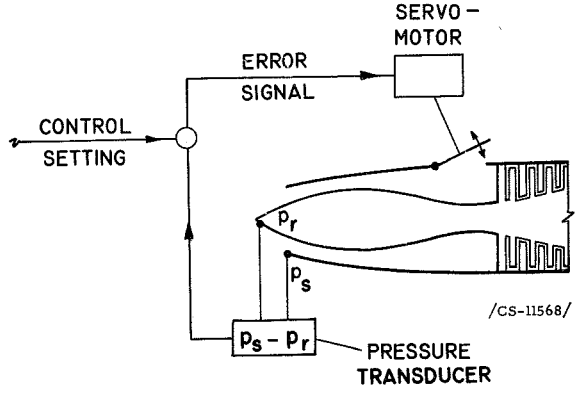

Figure 5a

NORMAL-SHOCK CONTROL OF BYPASS

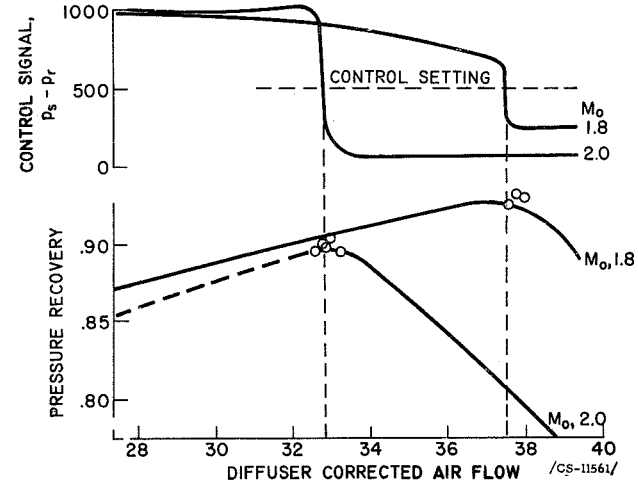

Figure 5b

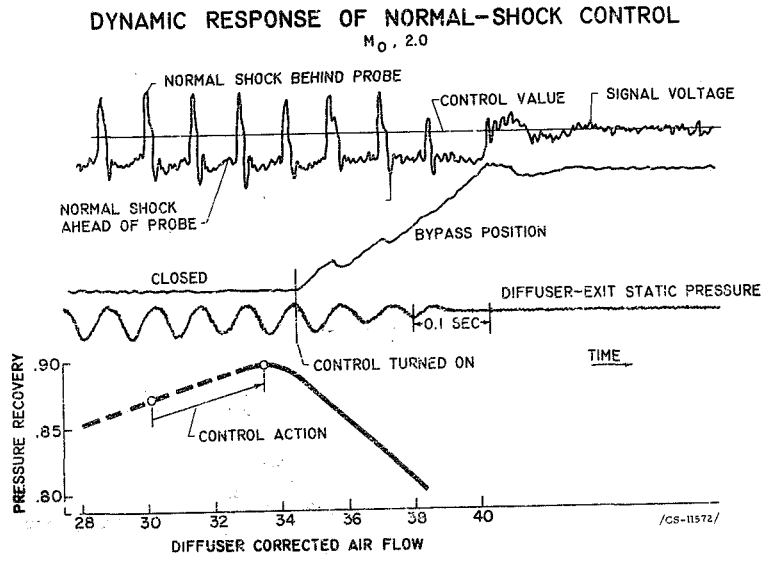

Figure 6

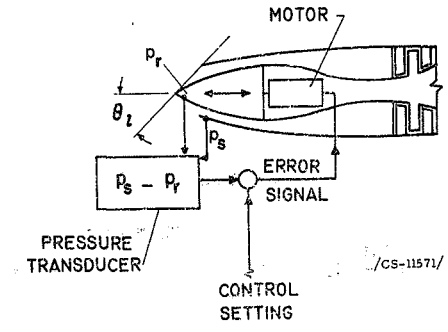

Figure 7a

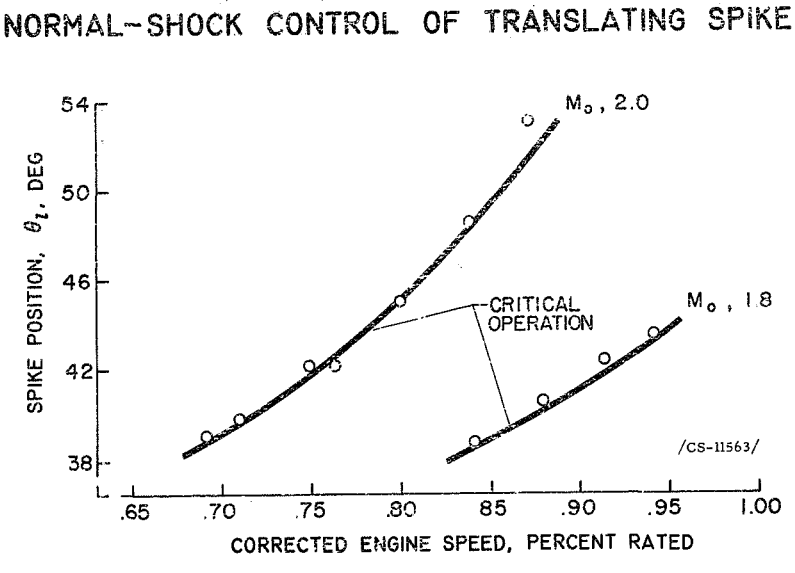

Figure 7b

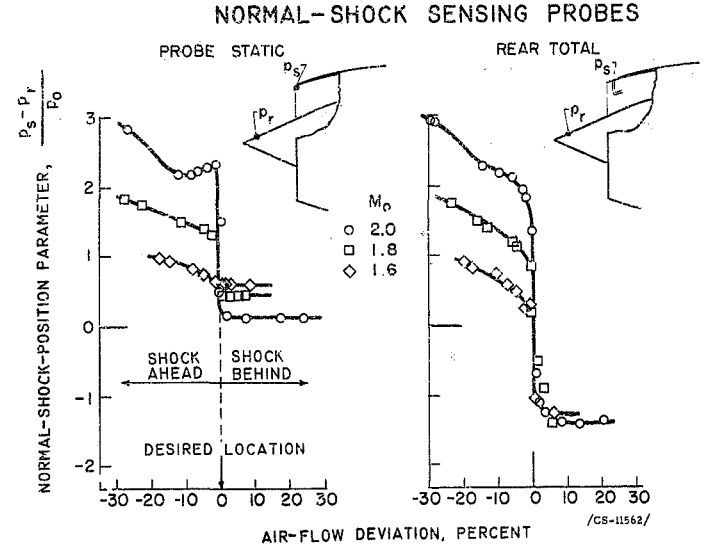

Figure 8

DIFFUSER RESPONSE TO BYPASS CHANGE

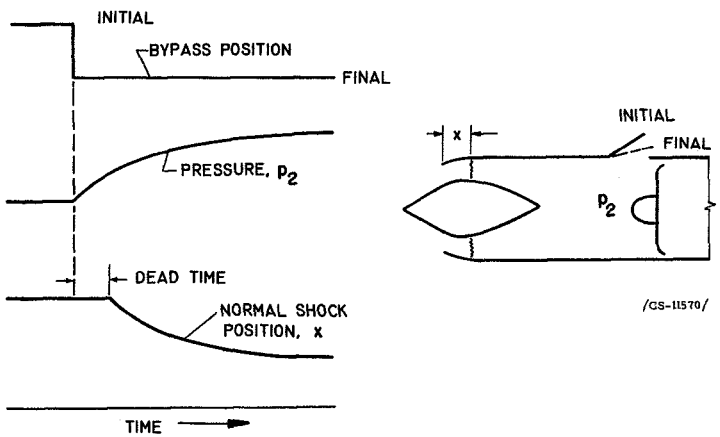

Figure 9

DIFFUSER CONTROL ERROR FOLLOWING ENGINE THROTTLE CHANGE

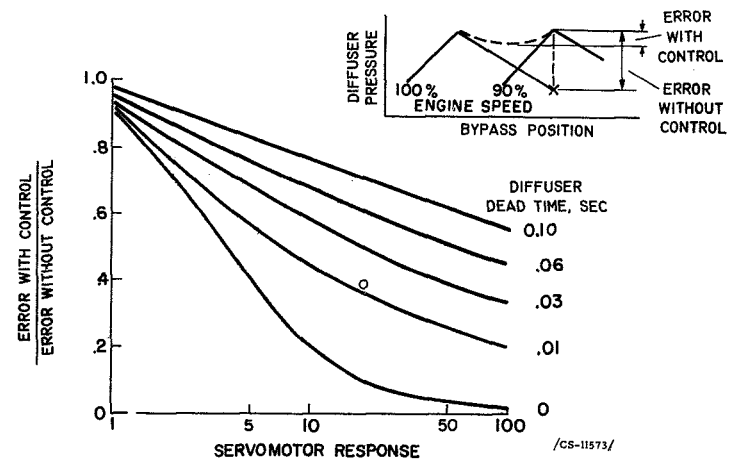

Figure 10